

# Quantitative evaluation and intercomparison of morning and afternoon Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol measurements from Terra and Aqua

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Received 4 May 2004; revised 1 July 2004; accepted 13 July 2004; published 10 February 2005.

[1] The quality of the aerosol optical thickness (AOT) data retrieved operationally from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua satellites, over land, and over ocean from 2000 to 2003 (Aqua only from June 2002) were evaluated thoroughly. Terra-MODIS versions 3 and 4 data (T003 and T004) and Aqua-MODIS version 3 data (A003) were independently and comparatively evaluated with collocated AOT from ground-based Aerosol Robotic Network (AERONET) Sun photometers. At 550 nm wavelength, 67.3%, 55.0%, and 55.5% of AOT from T003, T004, and A003, respectively, meet the prespecified accuracy conditions of  $\pm(0.05 + 0.2aot)$  over land, while about 63.3%, 59.4%, and 62.2% fall within the more stringent range of  $\pm(0.03 + 0.05aot)$  over ocean. However, when based on equal standards of comparison and regression analysis, aerosol retrievals are much more accurate over ocean than over land. Analysis of MODIS full regional AOT averages from 12 land and 6 oceanic regions shows that aerosol loading exhibits an annual cycle in almost every region, with the exception of very remote oceanic regions such as the central Pacific. On the basis of regional monthly averages, west Africa, China, and India show the highest peak monthly mean AOT value of  $\sim 0.7$  at 550 nm, while the highest over-ocean aerosol loading occurs over the Mediterranean and Mid-Atlantic oceans, with a regional monthly peak of  $\sim 0.35$ , which is half of the peak over land. The magnitude of day-to-day variation between morning (Terra) and afternoon (Aqua) AOT varies from region to region and increases with aerosol loading for any given region. However, none of the regions examined show any consistent regional trend in morning-to-afternoon aerosol loading, all showing almost equal likelihood of increase or decrease from morning to afternoon.

**Citation:** Ichoku, C., L. A. Remer, and T. F. Eck (2005), Quantitative evaluation and intercomparison of morning and afternoon Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol measurements from Terra and Aqua, *J. Geophys. Res.*, 110, D10S03, doi:10.1029/2004JD004987.

## 1. Introduction

[2] The Moderate Resolution Imaging Spectroradiometer (MODIS) twin sensors were launched under the auspices of the NASA Earth Observing System (EOS) program: the first on 18 December 1999 aboard the Terra satellite, and the second on 4 May 2002 aboard the Aqua satellite; and have both been measuring reflected and emitted radiance from the Earth and the atmosphere, day and night. Terra and Aqua, which are both polar-orbiting satellites, cross the equator during the daytime at approximately 1030 (morning) and 1330 (afternoon) local time (LT), respectively. Radiance data are acquired by MODIS in 36 spectral bands, spanning 405–14,385 nm wavelengths, which range from the visible (VIS) through the near-infrared (NIR) and midinfrared (MIR) up to the thermal infrared (TIR) regions of the electromagnetic spectrum. They are acquired in one of three spatial resolutions at nadir: 0.25 km (bands 1–2:

VIS), 0.5 km (bands 3–7: VIS-MIR), and 1 km (bands 8–36: VIS-TIR). MODIS data are being used operationally to generate a variety of geophysical parameters employed in monitoring the Earth's lands, oceans, and atmosphere. The products generated from MODIS are continuously being archived by appropriate NASA data centers and are distributed freely. The algorithms used to generate these products undergo periodic revisions, and data users are not always sure about the version and quality of the products they are using at any given time. It is, therefore, necessary to conduct periodic calibration and evaluation of the products to keep track of their evolution and make the information available to users.

[3] In this study, focus is on the MODIS aerosol products, which are retrieved at 10-km spatial resolution based on 0.25 and 0.5-km resolution reflectance data, with separate algorithms over land and ocean. The principal aerosol parameter from MODIS is the aerosol optical thickness (AOT or  $\tau_{a\lambda}$ ) retrieved over land at 470 nm and 660 nm wavelengths (then interpolated at 550 nm), and over ocean at 550, 660, 870, 1200, 1600, and 2100 nm (then extrapolated to 470 nm). Other important MODIS aerosol parameters include the proportion ( $\eta$ ) of AOT contributed by the aerosol fine mode fraction, Ångström exponent, emitted and reflected fluxes, and aerosol mass concentration, all derived over land and ocean; as well as aerosol effective radius derived over ocean

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only. Complete details of the original algorithms and parameters derived over land and/or ocean are given in the work of *Kaufman et al.* [1997] and *Tanré et al.* [1997], while the recent updates are described fully in the work of *Remer et al.* [2005].

[4] The purpose of evaluation, calibration, and validation is to detect biases, if any, originating from the processes involved in deriving the products, and to establish the accuracy levels of the products, based on comparison with independent observations of known accuracy (ground truth). In the case of measurement of global aerosols, the most well organized and well documented ground truth data sets are those observed under the banner of the Aerosol Robotic Network (AERONET) and other associated networks (e.g., Aeronet Canada (AEROCAN) and the French Photométrie pour le Traitement Opérationnel de Normalisation Satellitaire (PHOTONS)) [*Holben et al.*, 1998, 2001]. This network employs automatic Sun photometers/sky radiometers, which are located at over 100 sites worldwide, and whose data are regularly made available online by the AERONET team (<http://aeronet.gsfc.nasa.gov/>). Among other optically equivalent aerosol parameters, AOT data are derived from most AERONET Sun photometers at 340, 380, 440, 500, 670, 870, and 1020 nm wavelengths, while a few of their newer instruments also provide AOT at 532, 535, and 1640 nm. AERONET provides highly accurate AOT data, with uncertainty levels in the range of 0.01 to 0.02 (though slightly higher in the ultraviolet wavelengths) [*Eck et al.*, 1999]. Typically, AOT is measured at each AERONET site at least every 15 min during the daytime (under cloud-free conditions). It is, therefore, feasible and necessary to conduct periodic evaluation of the aerosol and other products, from both Terra and Aqua MODIS sensors, in a comparative and comprehensive manner.

[5] Results of early validation activities of the Terra-MODIS aerosol products using AERONET data were reported in the work of *Chu et al.* [2002], *Ichoku et al.* [2002], and *Remer et al.* [2002]. Subsequently, several important data filtering and algorithm improvement strategies and techniques were developed and implemented [*Gao et al.*, 2002; *Martins et al.*, 2002]. Results of some of the initial applications for global and regional studies have been published in the work of *Kaufman et al.* [2002], *Ichoku et al.* [2003], and *Levy et al.* [2003]. Indeed, the aerosol community has long begun using MODIS data quantitatively and extensively for regional and global aerosol pollution assessments, climate forcing calculations, and model comparisons [*Christopher and Zhang*, 2002; *Chu et al.*, 2003; *Yu et al.*, 2003; *Koren et al.*, 2004]. Details of the latest algorithm status and main changes, as well as longer-term validation results from Terra-MODIS have been described in the work of *Remer et al.* [2005]. Although the same aerosol algorithm is used for both Terra and Aqua MODIS processing, thus far, most of the published validation and other studies involving MODIS aerosol products used only Terra data, whereas only limited preliminary assessment has been conducted using aerosol products from Aqua MODIS [*Ichoku et al.*, 2004].

[6] In this paper, focus will be mainly on a comprehensive evaluation of Terra and Aqua MODIS spectral aerosol optical thickness  $\tau_{a\lambda}$ , which is the most important parameter from which others can be derived. Another major aspect of this study is to use the opportunity afforded by the availability of aerosol data from Terra and Aqua to study the patterns of aerosol distribution in the morning and after-

noon. The general design and scope of the current study will be described in section 2. Updated validation activities and results of MODIS  $\tau_{a\lambda}$  will be presented in section 3. A discussion of the main application-focused comparisons and synergisms between Terra and Aqua MODIS aerosol products at global, regional, and local scales will be given in section 4. The summary and conclusion will be presented in section 5.

## 5. Conclusions

[41] The spectral aerosol optical thickness  $\tau_{a\lambda}$  data, produced from Terra-MODIS and Aqua-MODIS from the beginning (2000 and 2002, respectively) up till the end of 2003, have been comprehensively and comparatively evaluated using AERONET data. The data sets evaluated were versions 3 and 4 from Terra-MODIS (T003 and T004) and version 3 from Aqua-MODIS (A003), which was retrieved with almost the same algorithm version as T004. Global assessment of  $\tau_{a550}$  from T003, T004, and A003, based on quality-assured (level 2.0) AERONET data, showed that about 67.5%, 55.0%, and 55.5% respectively, fall within the predefined uncertainty range of  $\pm(0.05 + 0.2 \tau_{a\lambda})$  over land, while about 63.3%, 59.4%, and 62.2%, respectively, fall within the more stringent over-ocean predefined range of  $\pm(0.03 + 0.05 \tau_{a\lambda})$ . For each of the data versions (T003, T004, and A003), the success rate appears to increase with wavelength at least for the evaluated 470 nm to 870 nm wavelength range. Furthermore, as the percentages above show, T003 is slightly more accurate than the later versions (T004 and A003) because these latter versions included retrieval over less than ideal situations such as over brighter surfaces on land. Over land, there is high likelihood of overestimation at low aerosol loading ( $\tau_{a550} < 0.20$ ), with about 55–65% of MODIS  $\tau_{a\lambda}$  retrievals falling within the predefined uncertainty bounds. The accuracy improves at moderate loading ( $0.20 < \tau_{a550} < 0.70$ ), with 70% or more of the retrievals at this range falling within the predefined uncertainty envelope. At high aerosol loading ( $\tau_{a550} > 0.70$ ) corresponding to less than 2% of the total retrievals, the accuracy fluctuates erratically. Over ocean, MODIS accuracy is high at low aerosol loading, with over 80% of the retrievals in the range of  $\tau_{a550} < 0.05$  falling within the uncertainty envelop. The over-ocean accuracy decreases as the aerosol loading increases. Although the global land and ocean percentages above seem comparable because of the more stringent tolerance over ocean, the respective correlation coefficients and regression slopes and intercepts show that the MODIS over-ocean retrievals are more accurate than over-land products. The main problems identified as influencing the over-land retrieval accuracy relate mainly to background land surface uncertainty due to surface variability, surface brightness, swamps, snow (especially at the melting stage). Other possible influences include scan angle dependence and neglecting to include polarization in the radiative transfer treatment. By contrast, the ocean retrieval, in addition to enjoying the benefit of a smoother dark (ocean) surface, which is favorable to aerosol retrieval (except over sun glint regions), also benefits from richer information content of the six wavelengths used directly for retrieval (as opposed to only two over land). Overall, the difference in performance between Terra and Aqua is not very significant.